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Reactor Simulator Integration and Testing

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September 2013

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LIST OF ACRONYMS AND SYMBOLS

ALIP	annular linear induction pump
GN ₂	gaseous nitrogen
HX	heat exchanger
N ₂	nitrogen
NaK	eutectic alloy of sodium and potassium liquid metals
PID	proportional-integral-derivative
RSF	reactor simulator function
RxSim	reactor simulator
TCP	Transmission Control Protocol
TDU	Technology Demonstration Unit

NOMENCLATURE

A	surface area of the core
c_{pc}	specific heat of the core
c_{pi}	specific heat of NaK at the core inlet
c_{po}	specific heat of NaK at the core outlet
c_{pt}	specific heat of NaK at the target temperature (set point)
\dot{m}	mass flow rate of NaK
m_c	mass of the core
T_c	cold wall temperature
$T_{\text{core}}^{\text{out}}$	reactor core outlet temperature
T_i	inlet temperature
\dot{T}_o	temperature rise rate set point
T_o	outlet temperature
T_t	target temperature (set point)
α_{coolant}	reactivity coefficient of the coolant
α_{fuel}	reactivity coefficient of the fuel
ΔT	initial temperature rise
ε	emissivity of the core
σ	Stefan-Boltzmann constant

TECHNICAL MEMORANDUM

REACTOR SIMULATOR INTEGRATION AND TESTING

1. INTRODUCTION

1.1 Background

A 40 kWe fission power system Technology Demonstration Unit (TDU) is being developed under the Fission Power Systems project. The TDU is composed of a non-nuclear core simulator, a sterling engine power conversion system, an annular linear induction pump (ALIP), liquid sodium/potassium (NaK) coolant, and radiator heat rejection. In support of TDU development, the reactor simulator (RxSim) test loop was developed to perform integrated component testing to verify operability prior to the TDU development. The RxSim was a NaK-filled test loop comprising a 37-pin reactor core simulator, NaK-gaseous nitrogen (GN_2) heat exchanger (HX) (for simulating the thermal load of the sterling power conversion system), an electromagnetic flow meter, and the TDU ALIP. In addition, although not part of the TDU, the RxSim had a secondary bypass loop across the ALIP to test a cold trap purification design. Figure 1 shows the RxSim layout. This Technical Memorandum covers testing in the RxSim loop; details of the design and development are in a separate report (J.B. Pearson, "Reactor Simulator Design and Build," unpublished data, 2013).

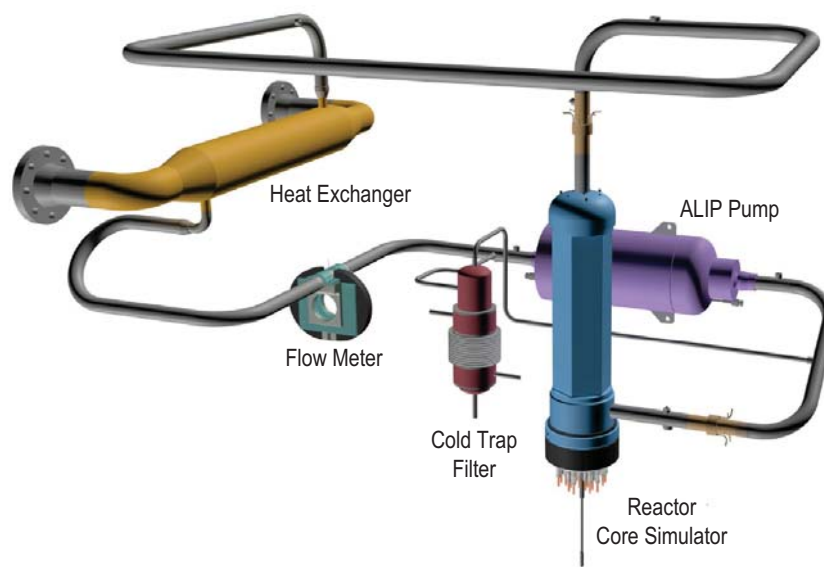


Figure 1. RxSim test loop layout.

2. REACTOR SIMULATOR OPERATION AND CONTROL

RxSim control systems were developed to provide the following five modes of operation: basic, power, power ramp, temperature, and reactor simulator function (RSF). Figure 2 shows the user interface panel for operating the RxSim.

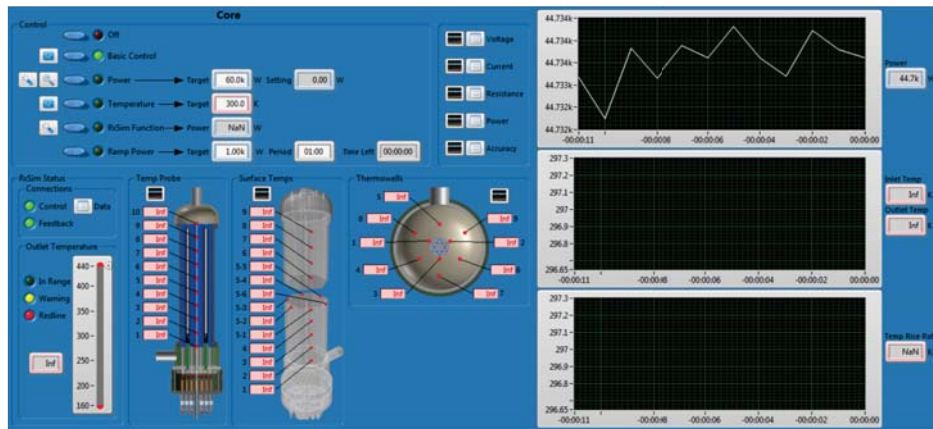


Figure 2. User interface panel for the RxSim control.

The basic control mode allows the operator to control the individual voltage and current settings for each of the 12 heater zones of the core simulator. Figure 3 shows the user interface panel for this control mode. This panel also provides a mechanism for calibrating the analog command used to control the current setting of each power supply.

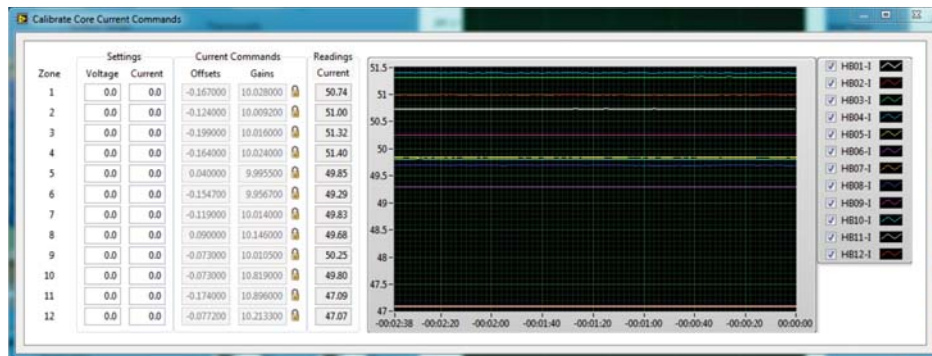
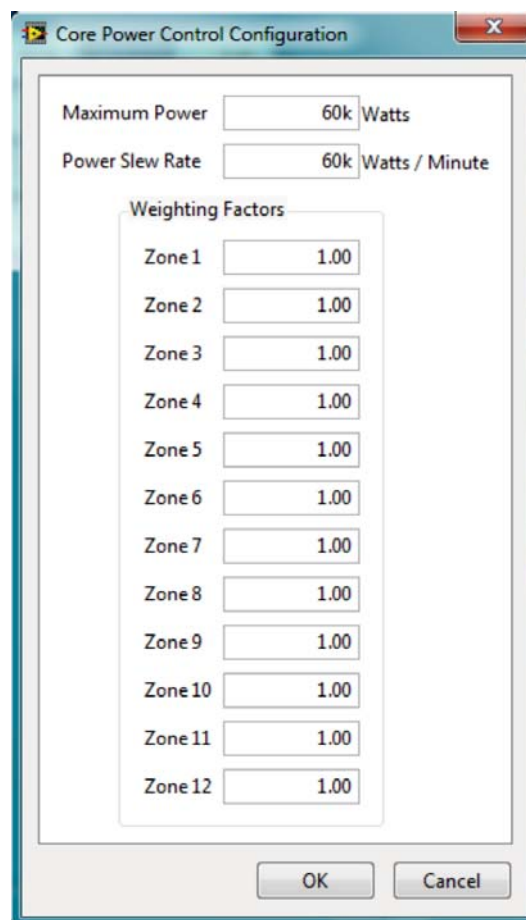


Figure 3. User interface panel for basic control mode.

Each of the 12 zones can operate in constant current or constant voltage mode depending on the voltage and current settings. When the load attempts to draw more current than the current setting, the constant current mode is enabled. Otherwise, the constant voltage mode is enabled. The voltage and current settings for each zone are limited to 150 V and 100 A, respectively.

The power control mode allows the operator to control the total power setting for the core. The power delivered to the core is distributed to each of the 12 heater zones according to weighting factors specified by the operator. For all operations to date, all weighting factors have been set to 1 so that the power is distributed evenly among all 12 heater zones. The power to a zone is controlled by operating its power supply in constant current mode. Current and voltage measurements for each zone are used to calculate the load resistance and the target set points required to achieve the desired power setting. As new measurements are taken, the current setting is adjusted to compensate for changes in the load resistance. When starting from a power setting of zero, the current and voltage settings of a zone are gradually increased until useable current and voltage measurements are obtained. The total power setting and power rate of change are limited and constrained by the maximum power and slew rate setting specified by the operator. The power control configuration dialog shown in figure 4 is provided for the operator to specify the maximum power, maximum slew rate, and weighting factors.



The image shows a software dialog box titled "Core Power Control Configuration". It contains three main sections: "Maximum Power" with a text box set to "60k" and the unit "Watts"; "Power Slew Rate" with a text box set to "60k" and the unit "Watts / Minute"; and a "Weighting Factors" section. This section contains a list of 12 zones, each with a text box set to "1.00". At the bottom of the dialog are "OK" and "Cancel" buttons.

Section	Parameter	Value	Unit
Power Limits	Maximum Power	60k	Watts
	Power Slew Rate	60k	Watts / Minute
Weighting Factors	Zone 1	1.00	
	Zone 2	1.00	
	Zone 3	1.00	
	Zone 4	1.00	
	Zone 5	1.00	
	Zone 6	1.00	
	Zone 7	1.00	
	Zone 8	1.00	
	Zone 9	1.00	
	Zone 10	1.00	
	Zone 11	1.00	
	Zone 12	1.00	

Figure 4. User interface for configuration settings of the core power control mode.

The power ramp control mode allows the operator to ramp the total power from a starting set point to a new set point over a specified period of time. Once the desired power is achieved, the control mode switches to the power control mode to maintain the new power setting. The ramp rate is limited by the maximum slew rate specified in the power control configuration dialog.

The temperature control mode allows the operator to control the NaK outlet temperature of the core. This mode uses two control loops to achieve temperature control. When the difference between the outlet temperature measurement and the set point is less than a specified limit, a temperature control loop is used. Otherwise, a temperature rise rate control loop is used. This ensures that the temperature does not rise or fall too rapidly when the difference between the measurement and set point are large. Each of the control loops combines a feedback (closed-loop) proportional-integral-derivative (PID) controller with a feed-forward (open-loop) control. The feed-forward control uses knowledge about the system to estimate the power setting required to achieve the desired set point, whereas the PID controller responds to differences between the set point and the actual measured temperature and adjusts the power setting to eliminate those differences. Although the open-loop estimate is not perfect, it does provide most of the power setting required to achieve the set point. The combination of the feed-forward control and the PID controller greatly improves overall system performance compared with the PID controller alone. The open-loop power setting estimates for temperature control are given by equation (1) and the temperature rise rate is given by equation (2):

$$\dot{m}(c_{pt}T_t - c_{pi}T_i) + A\epsilon\sigma(T_t^4 - T_c^4) \quad (1)$$

and

$$m_c c_{pc} \dot{T}_o + \dot{m}(c_{po}T_o - c_{pi}T_i) + A\epsilon\sigma(T_o^4 - T_o^4) . \quad (2)$$

To ensure bumpless transfer when the temperature control mode is activated and when switching between the temperature and temperature rise rate control loops, both loops continue to perform control calculations even when inactive. Figure 5 shows the user interface for tuning these control loops.

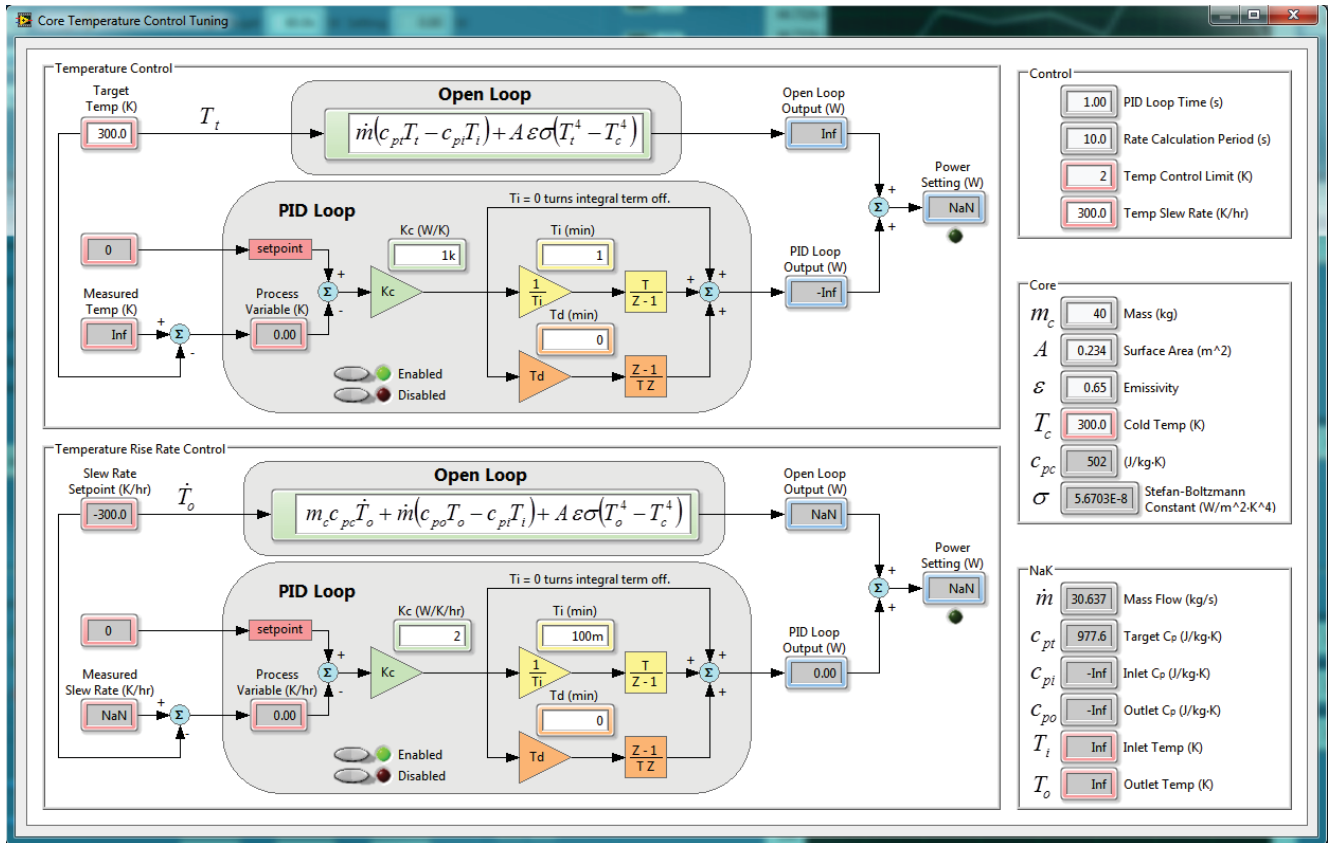


Figure 5. User interface for tuning temperature and temperature rise rate control loops.

The RSF mode enables remote control of the core power by a LabVIEW™ application running on a National Instruments cRIO-9024 real-time controller. The application runs a Simulink model that simulates the response of a real nuclear reactor. Two Transmission Control Protocol (TCP) network connections are used to communicate with the application. Feedback in the form of the core inlet temperature, NaK pressure, and NaK mass flow rate is provided to the application over one connection. The core power setting and various model outputs are returned over the other connection. The RSF mode can only be enabled when both TCP connections are active with no errors and when the core outlet temperature is within an operator-specified range. If either connection is lost or the outlet temperature goes out of range, the control mode switches to the temperature control mode to take the system back to the operator-specified temperature set point. Figure 6 shows the user interface for specifying the temperature limits and configuring the TCP communication.

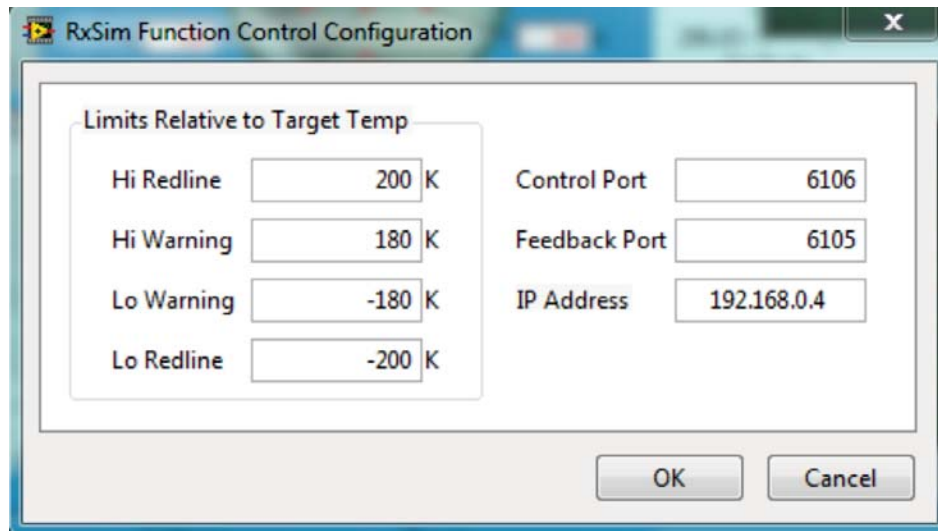


Figure 6. User interface for specifying temperature limits and TCP communication regarding the RxSim function control mode.

3. CONTROL FOR ANNULAR LINEAR INDUCTION PUMP OPERATION

Two modes of operation are provided for operating the ALIP: voltage and flow rate. Figure 7 shows the user interface for operating the ALIP.

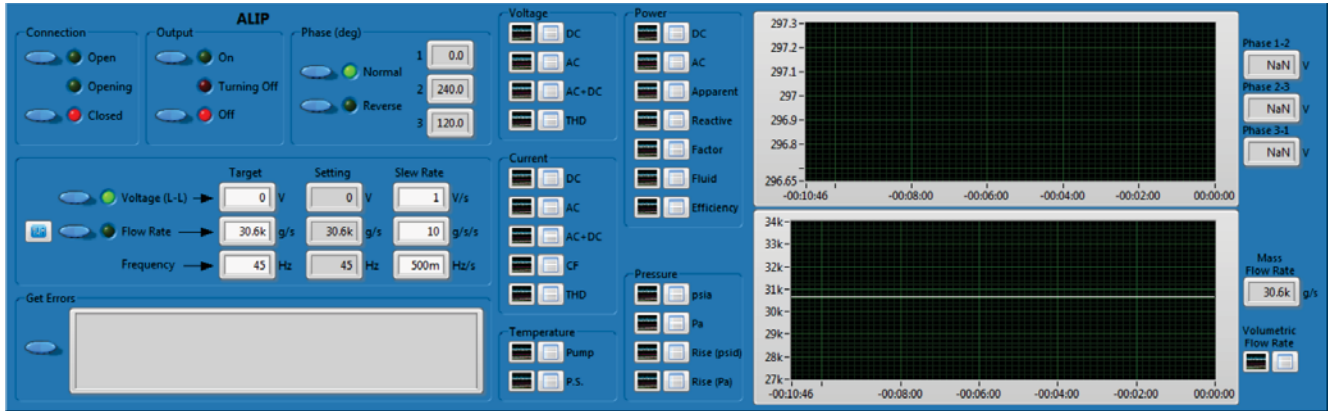


Figure 7. User interface for ALIP operation.

The voltage control mode allows the operator to control the line-to-line voltage setting of the ALIP power supply. To ensure that there are no abrupt changes in voltage while the pump is operating, new settings are limited by an operator-specified slew rate. The voltage setting is limited to 150 VAC.

The flow rate control mode allows the operator to control the NaK mass flow rate. This mode is implemented with a control loop that combines a feedback (closed-loop) PID controller with a feed-forward (open-loop) control. The feed-forward control uses knowledge about the system to estimate the voltage setting required to achieve the desired set point, whereas the PID controller responds to differences between the set point and the actual measured flow rate and adjusts the voltage setting to eliminate those differences. A linear curve fit of the measured flow rate at various voltage settings was used for the open-loop estimate. The differences due to nonlinearity and changes in temperature-dependent fluid characteristics were easily compensated for by the PID controller. The combination of the feed-forward control and the PID controller greatly improves overall system performance compared with the PID controller alone. To ensure bumpless transfer when flow rate control is activated, the control loop continues to perform control calculations even when inactive. Figure 8 shows the user interface for tuning these control loops.

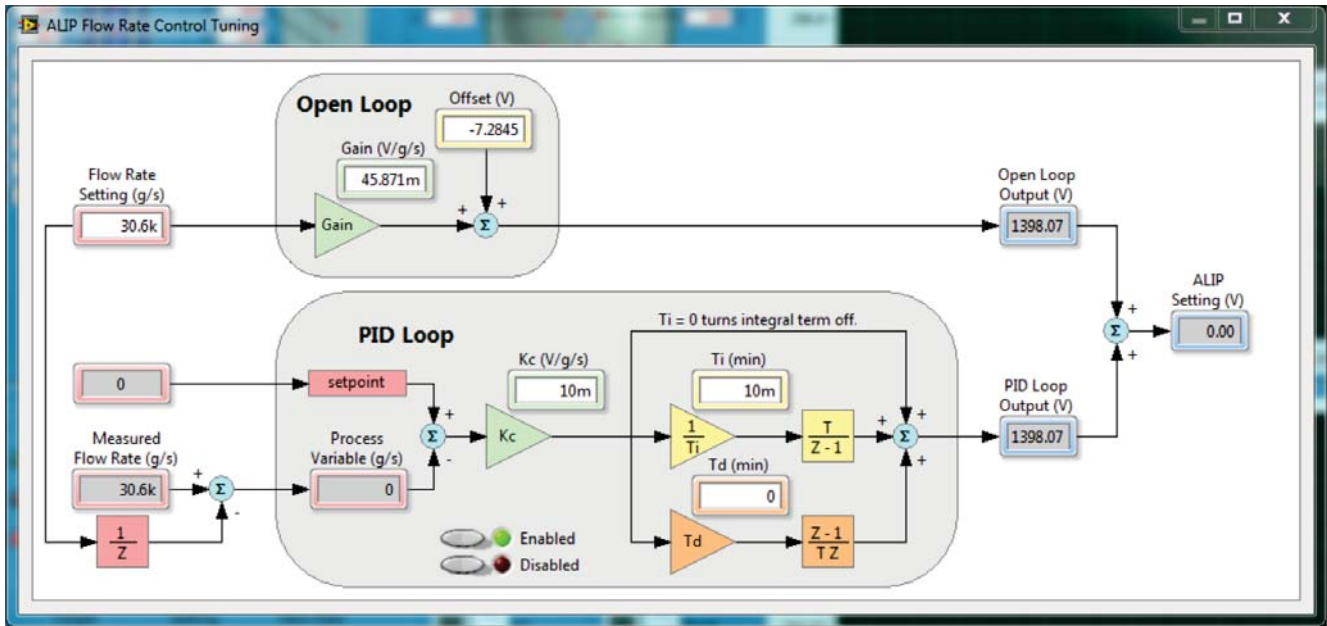


Figure 8. User interface for tuning ALIP operation control loops.

4. TESTING

RxSim testing involved operational checkouts of the loop control and instrumentation system, and the gas and vacuum test support equipment. To accomplish this, the RxSim was operated at TDU representative temperatures and flow rates (800 K and 1.75 kg/s). Vacuum and gas support equipment were used for NaK transfer operations (evacuating the RxSim loop, lower reservoir or accumulator, applying an argon pressure head, and actuating a remote operating valve). The gas system also supported the TDU ALIP by supplying and regulating (relief valve and regulator in conjunction) helium pressure in the electrical areas of the ALIP. In the past, this support equipment was provided by the test facility. These gas and vacuum racks were built to provide dedicated support equipment for the TDU. The vacuum and gas support equipment proved to be operational. The system's control and instrumentation program provided control algorithms to operate the loop at targeted core outlet temperatures and either mass flow rates or pump voltage. The control algorithms also controlled the slew rate within constraints. These algorithms proved to be sufficient and effective.

4.1 Reactor Simulator Heat-Ups, Steady State, and Transients

Figure 9 shows the effect of the control loop operation to constrain temperature ramp rates and maintain set point temperature. Figure 10 shows the control system responses to maintain a steady target temperature as perturbations are made to the RxSim loop during testing. Perturbations included changes in the NaK flow rate, the HX N₂ flow rate, and the temperature set point. The system performed well in controlling the target temperature over a wide range of operating conditions by controlling the rate of heat addition, which was provided by the core simulator. The control system autonomously controlled heat addition to counter balance the HX heat load that was manually controlled by the operator.

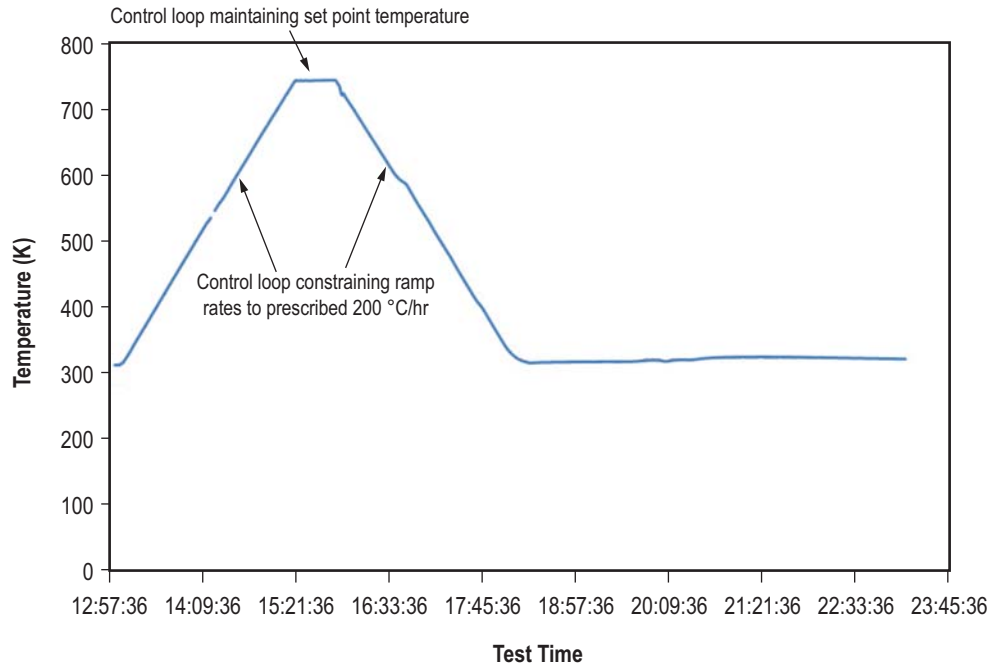


Figure 9. Example of temperature control mode operation.

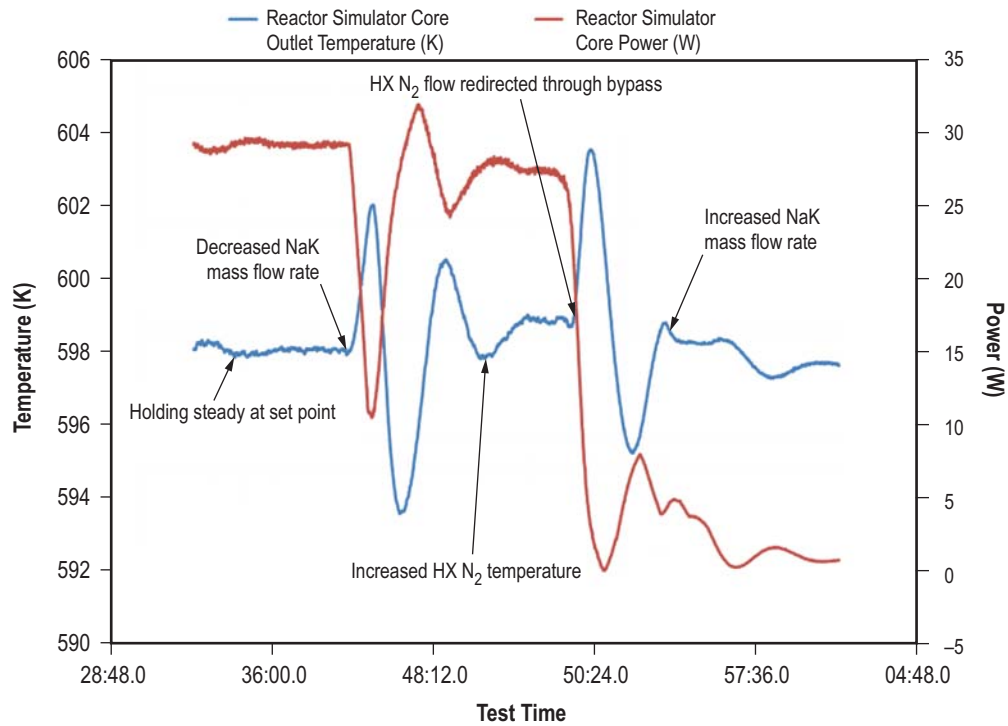


Figure 10. Example of temperature control mode response to RxSim loop perturbations.

Under certain conditions, instabilities could occur in the control system, as shown in figure 11. This was seen in circumstances when the time it took for temperature to respond, relative to changes in power input, was much longer than the control loop sample period, such as when operating at low flow rates. Controlling the temperature under these conditions would require the use of gain scheduling and an increase in the sample period. However, these conditions corresponded to operating regimes much different from nominal operation and did not pose difficulties for testing.

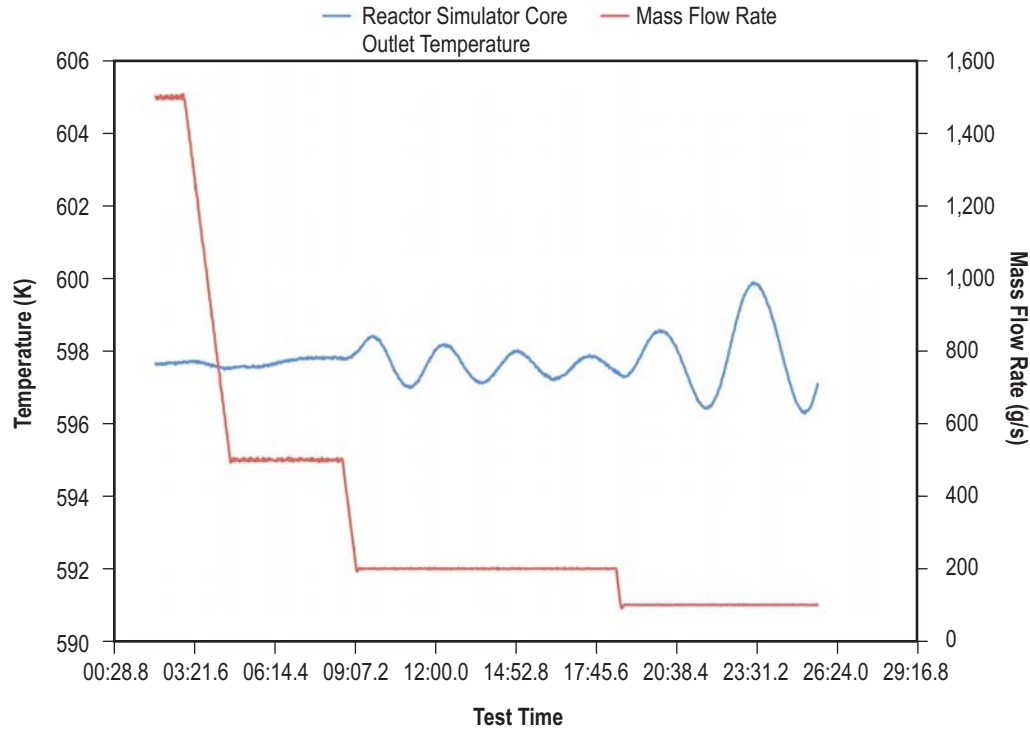


Figure 11. Example of the development of control instability. In this case, the instability resulted in an operating regime corresponding to slow mass flow rates.

4.2 Pump Testing: Maximum Permissible Flow

During the first series of tests, pump voltages and frequencies were ramped up and varied to achieve the maximum flow rate. It was found that the maximum flow rate obtainable in the RxSim loop with the TDU ALIP pump was about 1.33 kg/s (when the ALIP was provided 120 V at 55 Hz and a NaK temperature of 800 K). Thus, it was decided to extend the pump to a maximum of 150 V in which a maximum flow rate of 1.53 kg/s was obtained (fig. 12).

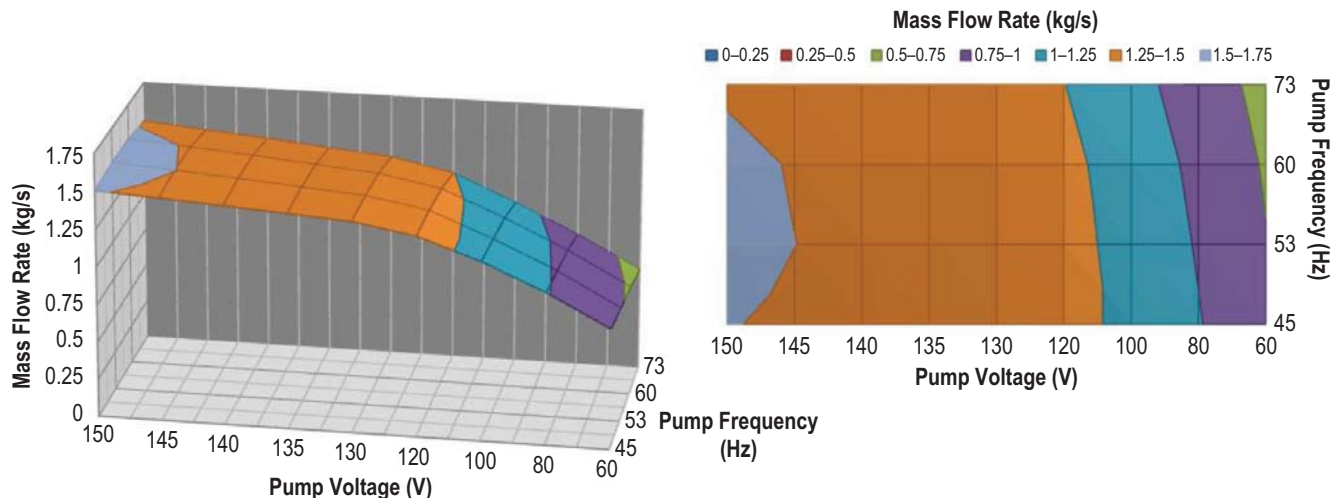


Figure 12. Expanded pump testing up to 150 V at $T_{\text{core}}^{\text{out}} = 800$ K. Maximum mass flow rate observed for the TDU ALIP in the RxSim test loop was 1.5 kg/s at 150 V and 73 Hz.

4.3 Cold Trap Thermal Test

The thermal performance of a cold trap design with heat regeneration was tested. The design, shown in figure 13, consisted of a bellows-jacketed GN_2 -NaK HX for cooling and accommodating thermal expansion. The NaK flow path consisted of a down-comer flow through alternating disk and donut baffles to create cross flow and increase NaK residing time within the cold trap. The volume between the baffles was packed with stainless steel wool to provide a reaction surface for oxide precipitation. The return flow path was through a tube running up the centerline of the cold trap and then terminating in a coil that was bathed in hot NaK from the inlet at the top of the cold trap. A cold temperature of 480 K was the targeted goal of the cold trap design, as analysis had indicated that purification of the NaK could be obtained within a reasonable period of time with this cold temperature. The analysis also indicated that a return flow through a coil would provide sufficient heat regeneration, so cold NaK would not be put back into the system acting as a thermal load. However, for this performance, the analysis indicated that a very slow NaK flow rate was required. The design proved to provide a good cooling capacity to reach a sufficiently low cold temperature with slow NaK flow rates as predicted. Heat regeneration was observed to occur more effectively within the cold trap return line than predicted, but not as effectively within the coil regenerator. An outlet temperature of about 750 K was predicted, but 636 K was observed.

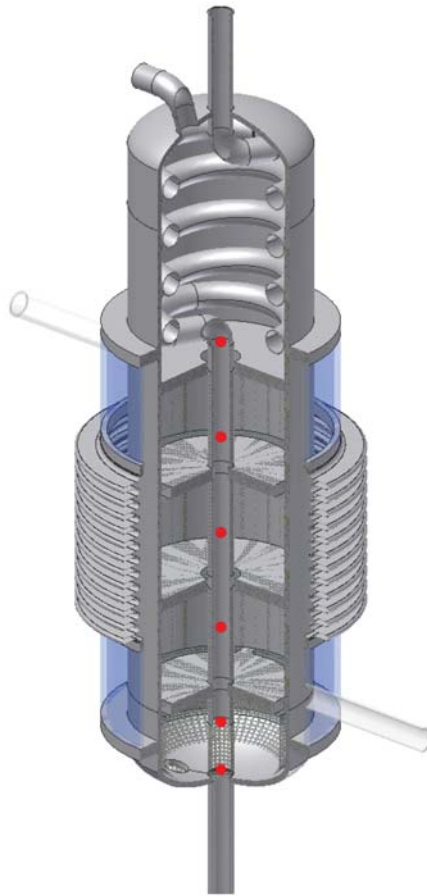


Figure 13. Cold trap design.

Figure 14 compares the cold trap thermal model and measured temperatures. The modeled flow rates were 0.00635 kg/s (NaK) and 0.078 kg/s (nitrogen (N_2)). The actual NaK flow rate through the cold trap was not measured, but in the primary loop it was 0.068 kg/s with the cold trap loop bypass valve open a quarter turn. The actual N_2 flow rates were not measured, but the supply pressure was 6 psi above ambient. The modeled inlet temperature was set to an actual cold trap inlet temperature of 800 K. The NaK and GN_2 mass flow rates were then tweaked to get modeled T_c approximately equal to measured T_c . The circles shown are model temperature predictions at locations expected to correspond with thermocouple probe locations, which are depicted as triangles.

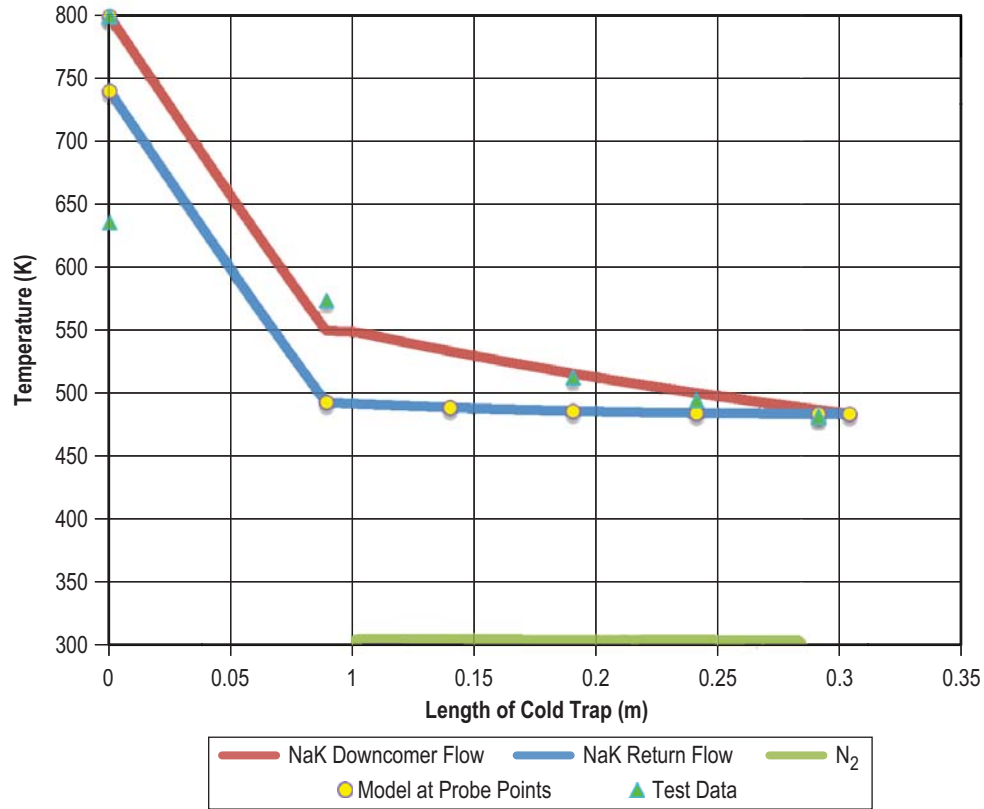


Figure 14. Cold trap performance.

4.4 Reactor Simulator Predictions and Interactions with RxSim Loop Control

Figure 15 shows the system behavior for a \$0.01 reactivity insertion. Figure 15(b) shows the model prediction of the transient. As an initial evaluation, the dampening behavior gives some indication that the simulation is reasonable. The predicted outlet temperature was based upon the initial conditions for inlet temperature and mass flow rate. For comparison, these were set to values of measured experimental data that correspond to figure 15(a), which shows the RxSim core outlet temperature during a transient driven by the reactor model simulator when utilizing the RxSim control function. Comparison between the measured/experimental outlet temperature (fig. 15(a)) to the predicted model/simulated outlet temperature (fig. 15(b)) shows close agreement and gives confidence in the RxSim model heat transfer calculations.

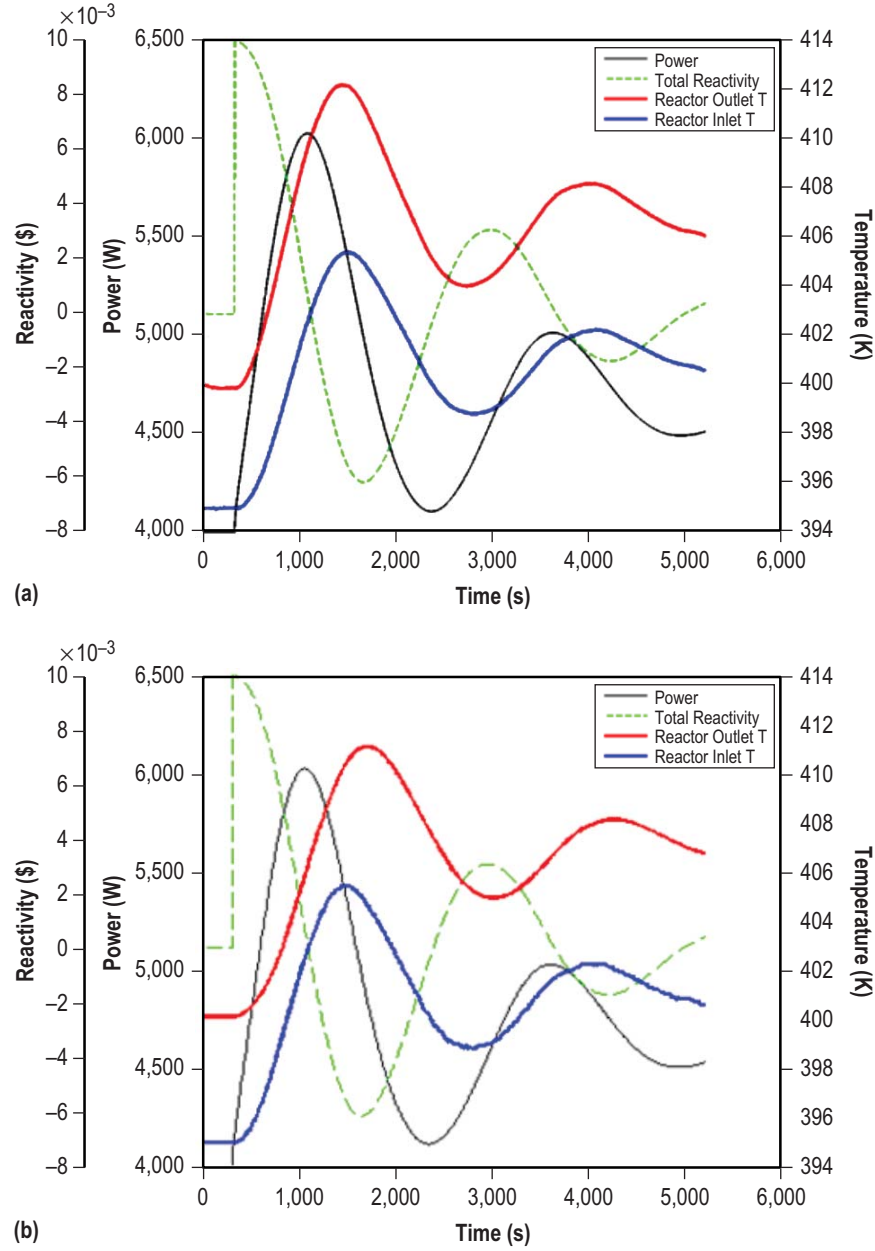


Figure 15. Comparison of RxSim behavior for a simulated \$0.01 reactivity insertion. Reactor outlet temperature in (a) corresponds to the measured experimental values while (b) corresponds to the simulated/predicted values.

Also, while debugging, three tests were run utilizing various reactivity feedback coefficients. In the three cases, the reactivity coefficients were set to one-eighth of the default values, the default values, and eight times the default values, respectively. The model default reactivity coefficients were $\alpha_{\text{fuel}} = -6.254 \times 10^{-4}$, and $\alpha_{\text{coolant}} = -9.09 \times 10^{-4}$. In each case, there was a \$0.02 reactivity insertion with the initial core power, outlet temperature, and ΔT of 20 kW, 450 K and 23 K, respectively. These tests demonstrated the RxSim loop would reflect the various possible system stability responses (stable, marginally stable, and unstable), as shown in figure 16.

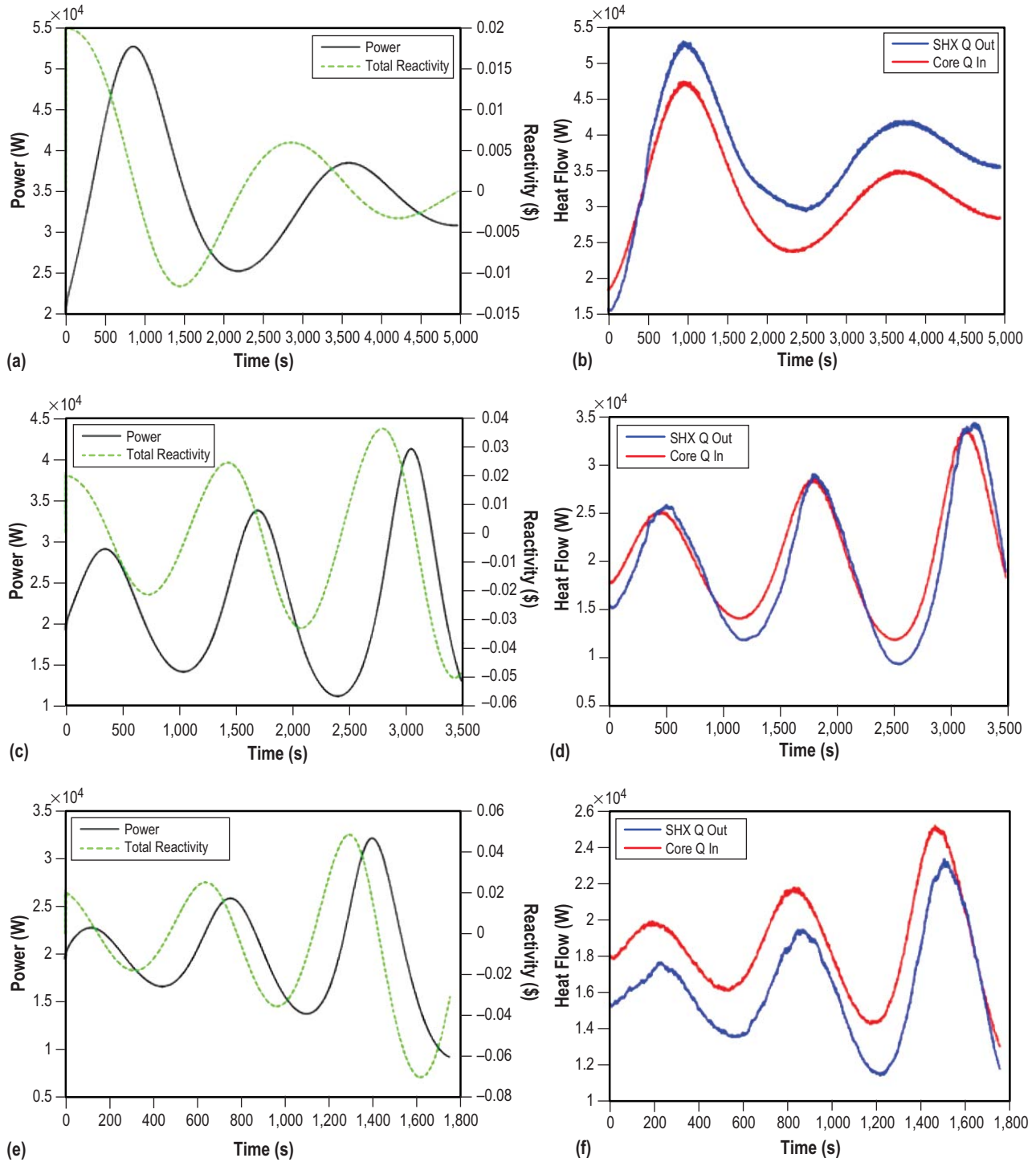


Figure 16. RxSim transient stability dependency on reactivity feedback coefficients:
 (a) Corresponds to a stable system due to (b) sufficient overcooling;
 (c) corresponds to a marginally stable system due to (d) a marginally cooled system; and (e) corresponds to (f) an unstable system response due to the system being undercooled.

5. CONCLUSIONS

Integrated testing of the TDU control and instrumentation, vacuum and gas ground test support equipment, and reactor core simulator components in the RxSim test loop demonstrated them to be operationally ready for TDU integration. The ALIP pump was found to not produce the desired flow rate for the RxSim test loop and is thus being considered as a backup pump for TDU testing. In addition, the heat regeneration design feature for cold trap purification was demonstrated with thermal testing of a cold trap integrated into the RxSim test loop. The RxSim model functionally integrated with the RxSim control loops to drive the RxSim system response in a manner more representative of nuclear reactor dynamics.

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14. ABSTRACT <p>As part of the Nuclear Systems Office Fission Surface Power Technology Demonstration Unit (TDU) project, a reactor simulator (RxSim) test loop was designed and built to perform integrated testing of the TDU components. In particular, the objectives of RxSim testing were to verify the operation of the core simulator, the instrumentation and control system, and the ground support gas and vacuum test equipment. In addition, it was decided to include a thermal test of a cold trap purification design and a pump performance test at pump voltages up to 150 V because the targeted mass flow rate of 1.75 kg/s was not obtained in the RxSim at the originally constrained voltage of 120 V. This Technical Memorandum summarizes RxSim testing. The gas and vacuum ground support test equipment performed effectively in NaK fill, loop pressurization, and NaK drain operations. The instrumentation and control system effectively controlled loop temperature and flow rates or pump voltage to targeted settings. The cold trap design was able to obtain the targeted cold temperature of 480 K. An outlet temperature of 636 K was obtained, which was lower than the predicted 750 K but 156 K higher than the cold temperature, indicating the design provided some heat regeneration. The annular linear induction pump tested was able to produce a maximum flow rate of 1.53 kg/s at 800 K when operated at 150 V and 53 Hz.</p>					
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